Development of a Smart Tool for Capturing Novel Advancement in Ballasted Rail Track Substructure

Hadi Khabbaz[1], Buddhima Indraratna[2]
1- A/Prof in Geotechnical Engineering, University of Technology, Sydney, Australia
2- Professor of Civil Engineering, University of Wollongong, NSW, Australia

Email: hadi.khabbaz@uts.edu.au

Abstract

The obligation of keeping a competitive edge against other means of transportation has increased the pressure on the railway industry to improve its efficiency and decrease the maintenance costs. In this paper, several innovative solutions are presented to improve the rail track foundations including optimum particle ballast grading and confining pressure as well as stabilising tracks overlying soft soils employing different techniques. A smart tool for predicting the performance of rail track substructure is also developed. This smart tool provides the user optimum construction parameters and required geotechnical properties according to various subgrade conditions, train loads and speeds.

Keywords: Rail track, ballast, smart tool, geosynthetics, track foundation.

1. INTRODUCTION

Rail track substructure, an essential component of the railway system, should be designed, built and maintained according to robust geotechnical principles and financially viable approaches. At present two types of rail tracks dominate railway systems: (1) slab track and (2) conventional ballasted track. Although conventionally ballasted track is the most common, some high speed railway systems have employed rigid concrete foundations. Recent studies [1, 2] indicate that slab tracks can be more cost-effective in some instances when life-cycle and maintenance costs are considered. Slab tracks are more suited to high velocity and high intensity traffic zones and especially where routine maintenance and traffic interruption are unfavourable or impracticable. The main advantages of a slab track design include, virtually free of maintenance, less traffic disruption, long service life, reduced dimensions and weight of substructure and no dust emission [1]. However, slab tracks have considerably higher initial construction and materials costs. Furthermore, slab tracks are required additional treatment and preparation for subgrade and in the case of structural damage or derailment it will be very costly and time consuming project [2]. The length of the rail network in many countries makes this option uneconomical. Hence, conventionally ballasted tracks keep on the most widely used option throughout the world; and its effective and efficient design remains a challenge for practicing engineers in rail industry.

Figure 1. Latite basalt used in New South Wales, Australia, as railway ballast

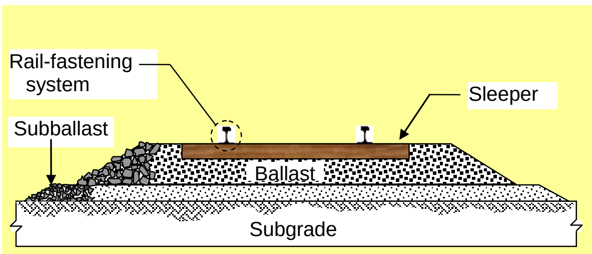

Figure 2. A typical ballasted railway track cross section indicating main components of rail substructure

Rail tracks founded on ballast (Figure 1) are relatively cost effective, have adequate drainage, and can easily be maintained. A conventional ballasted track is composed of differently graded layers of aggregates as shown in Figure 2. According to Selig and Waters [3] the ballast bed should undergo minimal plastic deformation (vertically, laterally and longitudinally) under dynamic loading due to the passage of trains, provide acceptable resiliency and sufficient energy absorption for the track structure, and transmit the imposed loading at an acceptable level to the subgrade. Additional functions include, efficient drainage of water from the ballast bed, retardation of the growth of vegetation and the ease of maintenance following construction [3-6]. However, for emerging tracks carrying faster passenger trains and heavier freight wagons, the conventional practice should be replaced by innovative track design and stabilisation.

In this paper problems associated with ballasted rail tracks are highlighted. Subsequently, key factors that can be taken into consideration to minimise the ballast related problems are explained. These factors are: (1) formation stabilisation, (2) effects of using geosynthetics in subgrade and capping layer, (3) better particle size distribution for ballast and sub-ballast to reduce settlement and ballast degradation, (4) optimised ballast and sub-ballast heights, (5) appropriate confining pressures to reduce truck buckling, and (6) reduction of sleeper-ballast stress concentration.

2. PROBLEMS ASSOCIATED WITH BALLASTED RAIL TRACKS

Ballast breaks down and deteriorates progressively under heavy train cyclic loads, settles differentially due to weak subgrade and poor drainage, fouls due to clay pumping and ballast breakage, and rail tracks buckles due to lack of confining pressure particularly during hot days in curved sections (Figures 3-9). These problems associated with track foundation result in costly rail track maintenance including ballast cleaning and replacement [2, 7-11]. Hence, an accurate quantification of mechanical behaviour of ballast, particularly at presence of under-lying soft soil formation [12, 13] is essential for stabilisation measures of railway tracks. On the other hand, the cost of substructure maintenance can be significantly reduced if a better understanding of the rail substructure behaviour is obtained.

Figure 3. Track fouls due to clay pumping [3]

Figure 4. Track fouls due to ballast degradation

Figure 5. Track settles differentially due to weak subgrade

The good quality railway ballast should have angular particles, high specific gravity, high shear strength, high toughness and hardness, high resistance to weathering, rough surface and minimum hairline cracks [14]. However, the sources of high quality ballast are limited, and under cyclic loading conditions, most ballast properties change progressively due to breakage, deformation and fouling.

The main causes of ballast degradation are excessive cyclic loading and vibration, temperature and moisture fluctuation, as well as impact load on ballast due to severe braking. The degradation of ballast particles can occur in three ways [4]:

- Grinding off of small-scale asperities (abrasion). The resulting fines cause fouling and reduce drainage.
- Breaking of fragments and angular projections, which influence the initial settlement.
- Fracturing or splitting of individual particles. This breakage is responsible for the long-term stability and safety of the track.

Experimental investigations (e.g. [5, 15-19]) show that the potential of particle breakage increases with ballast size. This is due to the fact that larger particles contain more flaws. Smaller particles are generally produced from larger particles fracturing along their defects. Therefore, smaller particles are less likely to fracture as they contain fewer defects. Increasing particle angularity increases particle breakage. Angular particles break more easily because stresses can concentrate along their narrow dimension or angular contact points, thus, breaking the particle.

Both monotonic [20] and cyclic tests [11, 19] on ballast specimens indicated that well-graded samples do not break as easily as uniform ones and also higher relative density reduces the amount of particle breakage. The degradation of ballast under loading has been observed in both wet and dry conditions [21]. Ballast experiences significant particle breakage upon saturation. Furthermore, the rate of particle breakage normally increases with increasing confining pressure. However, the effect of low confining pressure on ballast degradation is yet to be examined under cyclic loading.

Figure 6. Track buckling due to high temperature

Figure 7. Track needs increased lateral confinement during hot summer days

Figure 8. Soft soil formation and poor drainage

Generally, the main factors that affect ballast breakage can be divided into three categories [2]:

- Ballast properties related to the characteristics of the parent rock (e.g. hardness, specific gravity, toughness, weathering, mineralogical composition, internal bonding and grain texture)
- Physical properties associated with individual particles (e.g. soundness, durability, particle shape, size, angularity and surface smoothness)
- Factors related to the assembly of particles and loading conditions (e.g. confining pressure, initial density or porosity, thickness of ballast layer, ballast gradation, presence of water or ballast moisture content, cyclic loading pattern including load amplitude and frequency)

Figure 9. Waste and degraded ballast

Figure 10. Clay pumping and void clogging

Figure 11. Bulli track in NSW indicating ballast degradation

In the following section several novel approaches are presented to tackle the above mentioned problems and improve the rail track foundations.

3. METHODS TO IMPROVE THE BALLASTED RAIL TRACKS

New particle size distribution for ballast:

The ballast particle size distributions currently employed for railway lines are very uniform and contain only a small percentage of fine particles (i.e. particles less than 20 mm). Although a number of benefits of more well-graded distributions have been identified, such as, superior strength and reduced settlement [18, 22] they are rarely employed because of reduced drainage capacity and increased the risk of fouling.

In order to evaluate how slight changes in particle size distribution can affect the deformation and degradation behaviour of ballast, large-scale cyclic triaxial tests (Figure 12) were conducted on four different distributions of latite basalt, a type of ballast commonly used in New South Wales, Australia (Figure 1). The laboratory test results indicated that the use of a more appropriate gradation, which is slightly broader graded ballast than the current standards (Figure 13), provides denser packing, better frictional interlock and hence, less breakage and settlement.

Using geosynthetics for stabilizing the track:

A wide range of geosynthetics with different properties have been developed to meet highly specific requirements corresponding to various uses in new rail tracks and track rehabilitation for more than three decades. Enhancing the performance of rail tracks by composite geosynthetics is now seriously considered by rail industry. Based on relatively low cost and the proven performance of geosynthetics in a number of railway applications, University of Wollongong research team has conducted a comprehensive study to investigate the effects of the different types of geosynthetics on fresh ballast, recycled ballast, track drainage and stabilisation of railway formation [19].

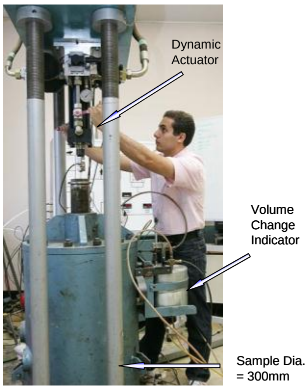

Figure 12. Large scale triaxial rig with a dynamic actuator designed and built at University of Wollongong

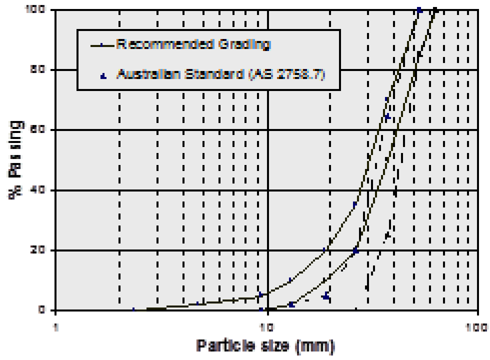

Figure 13. Recommended ballast gradation in comparison with current Australian Standard [2]

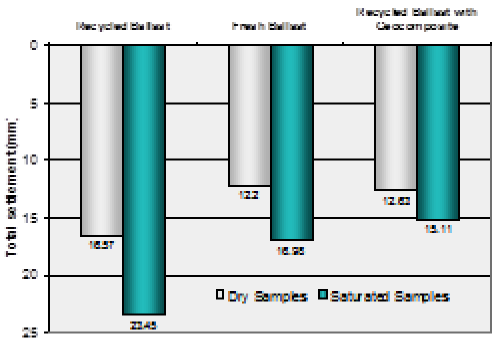

Figure 14. Settlement of dry and saturated samples after 500,000 load cycles [4]

Figure 15. Enhancing track performance by geotextile-geogrid composite [23]

It was expected that the use of geosynthetics would encourage the reuse of discarded ballast from stockpiles, reducing the need for further quarrying. The fundamental and experimental studies (Indraratna et al. 2003, 2004) in dry and saturated conditions proved that a geogrid bonded with a drainage fabric (geotextile) will increase the load bearing capacity of the ballast bed while minimising the lateral movement of ballast and reducing degradation as shown in Figures 14-16. Use of the composite geosynthetics also prevents the occurrence of liquefied soil and its upwards pumping that would foul the ballast.

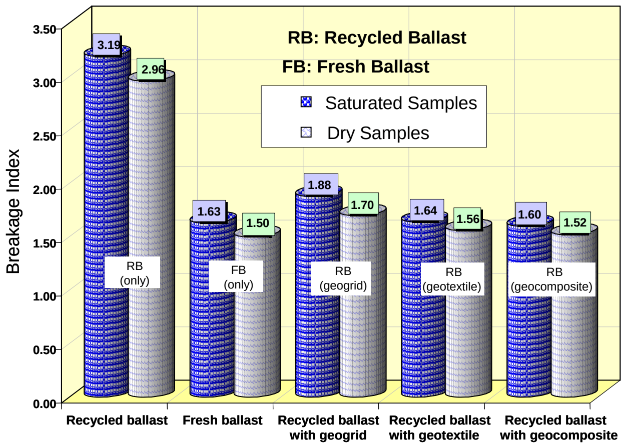

Figure 16. Breakage indices of ballast with and without geosynthetics

<u>Role of confining pressure on track behaviour:</u>

The effect of confining pressure on ballast shear strength, settlement and degradation is investigated based on monotonic and cyclic tests using large-scale cyclic triaxial apparatus [9]. Accordingly, the best possible ranges of confinement for various trainloads are determined. Enhancement of the lateral track confining pressure could be achieved practically by utilizing one or more of the following methods: (i) incorporating lateral restraints such as barriers at the extremities of the sleepers or shoulder ballast, (ii) increasing the sleeper-ballast frictional characteristics by changing the shape of the sleepers, reducing the sleeper spacing, or increasing the sleeper roughness, (iii) placing geosynthetic layers within the railway substructure, most suitably at the ballast-subballast interface [11], to promote interlock between the geosynthetics and ballast, and (iv) increasing the effective overburden acting on the load bearing ballast by utilizing greater ballast compaction during maintenance, compaction of the shoulder and crib ballast, or an increase in the height of the shoulder ballast.

<u>Soft formation stabilisation using vertical drains and native vegetation:</u>

Low-lying areas with high volumes of plastic clays can sustain high excess pore water pressures during both static and cyclic loading. The effectiveness of prefabricated vertical drains for dissipating pore water pressures and factors influencing its efficiency (e.g. smear effect) was investigated at University of Wollongong [25]. It was also shown that short prefabricated vertical drains may be used under rail tracks to dissipate cyclic excess pore pressure and to curtail lateral displacements to improve stability, if preloading is not used. However, where preloading can be applied, deeper soft formations can be stabilised using longer vertical drains, for more resilient soft soil foundations.

Tree roots provide three independent stabilising functions: (a) reinforcement of the soil, (b) dissipation of excess pore pressure and (c) establishing matric suction increasing the soil shear strength. The matric suction established in the root zone propagates radially and contributes in ground stabilisation near the root zone [26]. Using native vegetation in semi-arid climates and coastal regions of Australia has become increasingly popular for stabilising railway corridors built over expansive clays and compressive soft soils.

3. TRACK SMART TOOL FOR DESIGN AND MAINTENANCE OF RAILWAY SUBSTRUCTURE

A smart tool for predicting the performance of rail track substructure has been developed for capturing the findings of geotechnical aspects of rail tracks. This smart tool provides the user the optimum construction figures and required geotechnical properties according to various subgrade conditions, train loads and speeds. This tool can be a viable professional-level package as a ‘one-stop shop’ providing independent advice and design outputs for the construction of new rail tracks and improving maintenance of existing tracks. Figures 17 to 23 are demonstration some capabilities of this program. The programming language MATLAB (version 7.5) was used to create this rail track design tool.

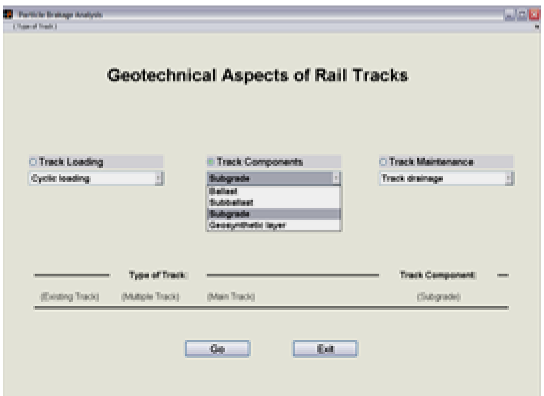

Figure 17. Main page of the Track Smart Tool

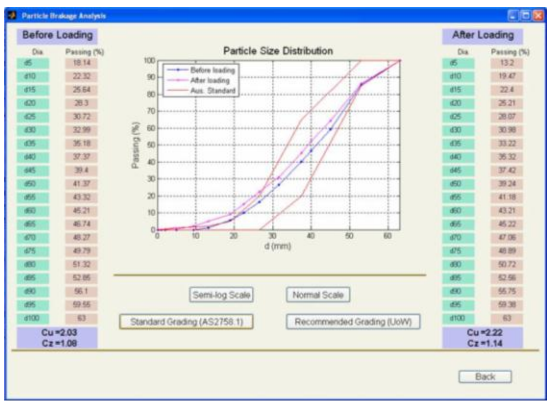

Figure 18. Ballast particle size distribution (before and after loading plus the standard grading)

Some features of this program are: (i) calculating the height of ballast layer based traffic conditions, rail and sleepers properties, ballast and subgrade characteristics and proposed design criteria such as allowable plastic stain and allowable deformation. The design is mainly following the Li and Selig’s model presented in 1998 [7, 8]. However other conventional design methods [27] including Talbot (1919), Clarke (1957) Schramm (1961), Eisenmann (1970), and Japanese National Railways (1961) were implemented. It was decided that the addition of other forms of ballast design was an appropriate addition to this program, as it would increase the usefulness of the program for practicing engineers by allowing them to easily perform existing forms of analysis with which they were already comfortable and could be confident in the results of. Addition of these methods also facilitates the current addition of numerical finite element methods, and allows comparison of these new methods to existing tried-and-tested routines; (ii) calculating ballast breakage indices using the most common methods; (iii) determining ballast breakage, axial strain and settlement under various confining pressures and deviator stresses; (iv) evaluating the ballast grading after and before a certain number of loading against the standard and recommended ranges of ballast particle distributions; (v) calculating ballast properties, drainage and fouling index before and after loading.

4. USING AN EXPERT SYSTEM TO INTEGRATE THE FINDINGS OF CURRENT RESEARCH

Expert Systems are advanced computer programs that manipulate knowledge and expertise to solve problems efficiently and effectively in a specific problem domain. An expert system contains three main components: knowledge base user interface inference engine as shown in Figure 24. Expert systems work with information, based on robust probabilities, whereas conventional programs work with data, based on algorithms. The main differences between these two approaches are summarised in Table 1.

Table 1- Conventional programs versus expert systems

Conventional Programs	Expert Systems
Algorithmic	Heuristics (*an appropriate solution based on alternative methods*)
Right/Wrong	Probability (*uncertainty is taken into account)*
Static	Evolving (*does not degrade over time as the knowledge is kept up to date)*
Works with Data	Works with information *(accept facts, rules, expert consultations etc.)*

The main goal of this research is to develop an expert system providing independent assessment and advice on geotechnical aspects of rail tracks including: ballast, sub-ballast and formation. This stage of research is currently carrying out to implement available information, facts, rules, standards and the state of the art investigations collected from recent cutting edge studies, rail industry experts and worldwide experiences. We are assembling the experimental results, numerical analysis findings and existing field data in the program. This program will be validated using the published case histories, laboratory data and field measurements. It is envisioned that once development is taken place, this expert tool will become a viable professional level package for the complete design and remediation of railway ballast worldwide. However, It can be noted that expert systems are considered as decision support tools or "assistants", rather than pretending that they could replace engineering expertise.

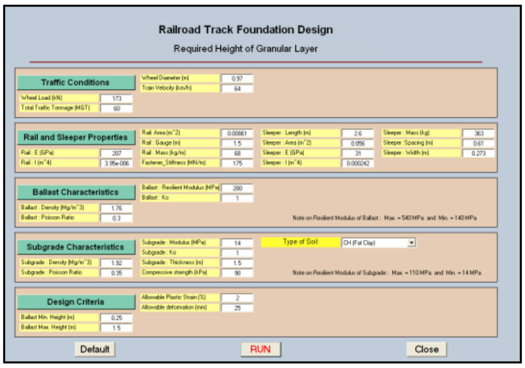

Figure 19. Rail road foundation design part of the developed track smart tool

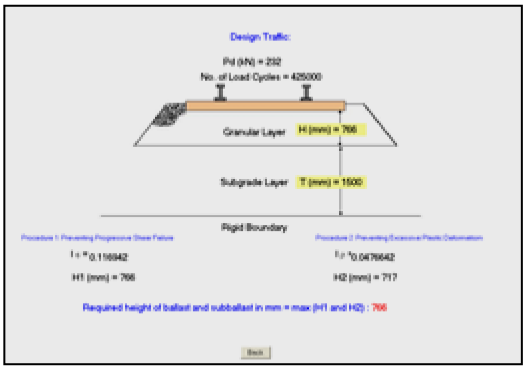

Figure 20. A typical result produced by the program developed by the authors

5. CONCLUSIONS

The common problems with ballasted tracks, discussed in this paper, are the progressive deterioration of ballast particles, differential settlement, fouling of ballast, pumping of clay the high lateral movement of ballast and track buckling and poor subballast drainage. The research findings show that the ballast deformation and breakage can be reduced if appropriate ballast grading and track confining pressure are applied. The bonded geogrids can improve the performance of ballasted tracks. It is also indicated that that prefabricated vertical drains can be used when accelerated rate of consolidation and improvement of soft formation of rail track is desired. Native vegetation can also improve the conditions of soft soil formation in the vicinity of rail tracks. The role of different types of geosynthetics in reducing degradation and excessive track deformation of fresh and recycled ballast is highlighted.

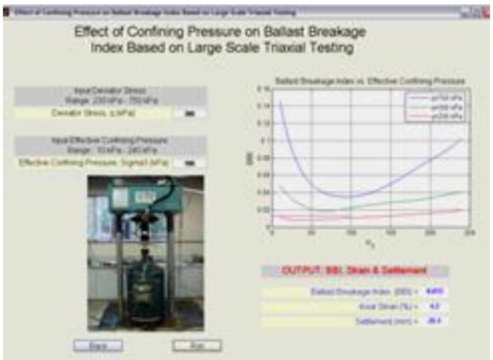

Figure 21. Effect of confining pressure on ballast breakage and settlement

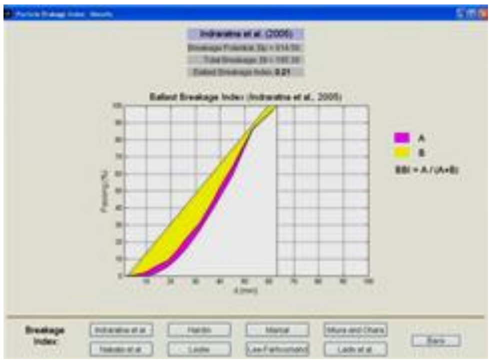

Figure 22. Different approaches to calculate ballast breakage index

Rail Track Geomechanics is a domain in which it would require a number of years experience to become expert. The developed track smart tool provides valuable aids to make decisions more quickly and more easily at reduced costs. This tool has been developed to incorporate various aspects of rail substructure, combining UoW research results and rail industry knowledge. The current stage of this ongoing research is to develop a comprehensive expert system to integrate numerical analysis results, laboratory and field trial data, research papers and reports, case studies and historical records, practicing engineers' experience, expert consultations, rail track substructure databases, and other related information.

Figure 23. Ballast permeability and fouling index

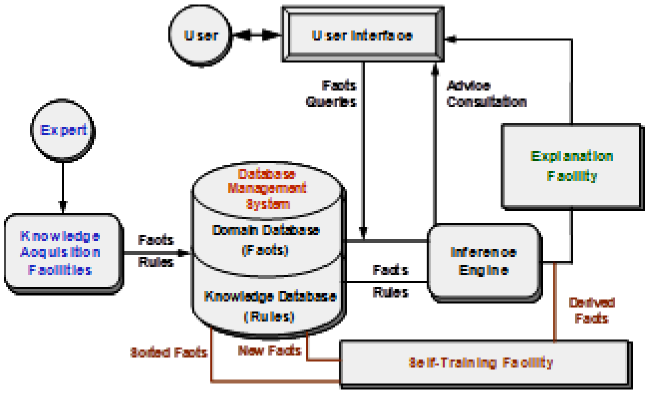

Figure 24. Architecture and main features of an expert system

6. ACKNOWLEDGMENT

The authors acknowledge the financial support of the Cooperative Research Centre for Railway Engineering and Technologies, Australia. They express their special thanks to former and current research fellows and PhD students at University of Wollongong for their assistance and contribution to this research project. The authors also wish to acknowledge the support and cooperation of rail industry colleagues David Christie of RailCorp, Mike Martin of Queensland Rail, Julian Gerbino of Polyfabrics Australia and Wayne Patter of Australian Rail Track Corporation (ARCT).

7. REFERENCES

1. Esveld, C. (2001). "*Modern Railway Track*" (Second Edition), MRT-Productions, Netherlands.
2. Indraratna, B., Khabbaz, H. and Salim, W., (2006), "Geotechnical properties of ballast and the role of geosynthetics", Journal of Ground Improvement, ISSMGE, **10** (3), pp 91-101.
3. Selig, E. T. and Waters, J. M., (1994), "*Track Geotechnology and Substructure Management*", Thomas Telford Services, London, UK.
4. Indraratna, B., Khabbaz, H., Salim, W., Lackenby, J. and Christie, D., (2004), "Ballast characteristics and the effects of geosynthetics on rail track deformation", International Conference on Geosynthetics and Geoenvironmental Engineering, Mumbai, India, pp 3-12.

5. Indraratna B., Khabbaz H., Salim W. and Christie D., (2003), "Geotechnical characteristics of railway ballast and the role of geosynthetics in minimising ballast degradation and track deformation", RAIL-TECH 2003, Railway Technology in the New Millennium, Kuala Lumpur, pp 3.1-3.22.
6. Indraratna, B., Salim, W. and Christie, D., (2002), "Improvement of recycled ballast using geosynthetics", 7th Int. Conf. on Geosynthetics, Nice, France, pp 20-29.
7. Li, D., and Selig, E. T., (1998), "Method for Railroad Track Foundation Design I: Development", Journal of Geotechnical and Geoenvironmental Engineering, **124** (4), pp 316-322.
8. Li, D., and Selig, E. T., (1998), "Method for Railroad Track Foundation Design II: Applications", Journal of Geotechnical and Geoenvironmental Engineering, **124** (4), pp 323-329.
9. Indraratna B., Lackenby J. and Christie D., (2005), "Effect of confining pressure on the degradation of ballast under cyclic loading", Geotechnique, **55** (4), pp 325-328.
10. Salim, W. and Indraratna, B., (2004), "A new elasto-plastic constitutive model for granular aggregates incorporating particle breakage", Canadian Geotechnical Journal, **41**, pp 657-671.
11. Salim, W. (2004), "*Deformation and Degradation Aspects of Ballast and the Role of Geosynthetics in Track Stabilisation*", PhD Thesis, University of Wollongong, Australia.
12. American Railway Engineering and Maintenance-of-Way Association (AREMA), (2003), "*Manual for Railway Engineering*", USA.
13. AS 2758.7, (1996), "*Aggregates and Rock for Engineering Purposes*", Australian Standard, Part 7: Railway Ballast, Australia.
14. Indraratna, B., Ionescu, D. and Christie, D., (1998), "Shear behaviour of railway ballast based on large-scale triaxial tests", Journal of Geotechnical and Geoenvironmental Eng., ASCE, **124** (5), pp 439-449.
15. Lade, P. V., Yamamuro, J. A. and Bopp, P. A., (1996), "Significance of particle crushing in granular materials", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **122** (4), pp 309-316.
16. Hardin, B. O., (1985), "Crushing of soil particles", Journal of Geotechnical Eng., **111** (10), pp 1177-1192.
17. Charles J. A. and Watts K. S., (1980), "The influence of confining pressure on the shear strength of compacted Rockfill", Geotechnique, **30** (4), pp 353-367.
18. Jeffs, T., and Marich, S., (1987), "Ballast characteristics in the laboratory", Proc. Railway Engineering. Conf., Perth, Australia, pp 141-147.
19. Indraratna, B. and Salim, W., (2005), "*Mechanics of Ballasted Rail Tracks - A Geotechnical Perspective*" A. A. Balkema, Taylor and Francis. UK.
20. Marsal R. J., (1967), "Large scale testing of rockfill materials", Journal of Soil Mech. and Foundation. Engineering, ASCE, **93** (SM2), pp 27-43.
21. Indraratna, B. and Salim, W., (2003), "Deformation and degradation mechanics of recycled ballast stabilised with geosynthetics", Soils and Foundation, **43** (4), pp 35-46.
22. Raymond, G. P., (1985), "Research on railroad ballast specification and evaluation", Transportation Research Record 1006 - Track Design and Construction, Canada, pp 1-8.
23. Martens, A., (2002), "Use of geosynthetics in railway construction", Proc. 7th Int. Conf. on Geosynthetics, International Schienen der Welt, 22-27 Sep., Nice, France, Cover Photograph.
25. Attya, A., Indraratna, B. and Rujikiatkamjorn, C., (2007), "Effec-tiveness of vertical drains in dissipating excess pore pressures induced by cyclic loads in clays", Proceedings of the 16th Southeast Asian Geotechnical Conference, Yee, K, et al. (eds), Selangor, Malaysia, pp 447-451.
26. Indraratna, B., Fatahi, B. and Khabbaz, H. (2006), "Numerical analysis of matric suction effects of tree roots", Proc. of the Institution of Civil Engineers Geotechnical Engineering, **159** (2), pp 77-90.
27. Jeffs, T., Tew, G. P., (1991), "*A Review of Track Design Procedures Volume 2: Sleepers and Ballast*", Railways Austraia, Melbourne. Australia.